A HIGH-Q SOLID DISK BAW GYROSCOPE IN MONOCRYSTALLINE 4H SILICON-CARBIDE WITH SUB-PPM AS-BORN FREQUENCY SPLIT

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ABSTRACT

This paper demonstrates, for the first time, a solid disk capacitive bulk-acoustic wave (BAW) gyroscope in monocrystalline 4H-SiC, with a promising angle random walk of 0.03°/√h, fabricated at wafer level using DRIE of a bonded SiC-on-Insulator (SiCOI) substrate. The 3MHz gyroscope operates in m=3 elliptical mode with a very small as-born frequency split of sub-ppm owing to the excellent in-plane isotropic lattice of 4H-SiC. Statistical data of resonator characterization across the 4-inch SiCOI wafer is reported, showing consistently small frequency splits and high *Q* factors, uncommon in Si substrates. The cross-coupling between two gyroscopic modes is compensated via electrostatic spring softening, while the 3mm disk resonator is driven to >300nm amplitude, paving the way towards the development of high-performance SiC BAW gyroscopes.

KEYWORDS

Silicon carbide resonator, *Q* factor, MEMS gyroscope, novel substrate for MEMS resonator

INTRODUCTION

Over the past decades, high-performance gyroscopes for inertial navigation have drawn much attention owing to the growing market in autonomous vehicles, indoor navigation, and dead reckoning [1]. Navigation grade gyroscopes require vibration immunity, large dynamic range, high signal-to-noise-ratio (SNR), and small bias instability, making traditional low-frequency large-mass tuning fork gyroscopes unsuitable. Instead, bulk acoustic wave (BAW) resonant gyroscopes with high mechanical stiffness operating in the megahertz range have been proven to be a promising design to meet the above requirements [2~5]. Due to their resonant (i.e. mode-matched) operation, where the frequencies of two gyroscopic modes overlap, the scale factor and SNR of a BAW gyroscope are amplified by the mechanical *Q* factor. To date, the BAW resonators in single crystalline silicon substrates have already achieved *Q* factors near its physical limit set by the Akhiezer damping [6,7]. Earlier this year, Qualtre Panasonic reported on a capacitive BAW gyroscope in (100) silicon with a bias instability of 0.25°/hr operating in closed-loop configuration that extended the device bandwidth to greater than 200Hz [8].

Looking beyond silicon, monocrystalline 4H silicon carbide-on-insulator (4H-SiCOI) substrate is a promising platform for the implementation of inertial-grade MEMS gyroscopes owing to SiC's exceptionally high Akhiezer limit which dwarfs that of Si by ~30× [6,7,9]. Moreover, the hexagonal crystal symmetry of 4H-SiC is amenable to excellent mode degeneracy between the m=3 BAW gyroscopic elliptical modes in disk resonators. Some recent works have shown that m=3 modes of capacitive disk resonators in 4H-SiC exhibit ultra-low dissipation levels ($Q > 3\times10^6$), and as-born frequency splits near 13 ppm [10,11]. In fact, mechanical *Q*'s up to 20×10^6 have been reported in 4H-SiC disk and lamé mode resonators [11]. However, SiC is a hard to etch material, and its precision DRIE with high aspect ratio had not been demonstrated until very recently [12~15], at odds with electrostatic tuning, which usually require small capacitive gap for effective mode matching and alignment of resonant gyroscopes. This paper will show the great potential of the 4H-SiC substrate for gyroscope application. In particular, with statistical data of small as-born mode split in disk resonators fabricated at wafer-level, mode-matching, including quadrature cancelation, was demonstrated despite the relatively large capacitive gaps. For the first time, gyroscope performance of 4H-SiC BAW disk resonator with DRIE capacitive transducers is reported, paving the way towards navigation-grade performance and beyond using SiC BAW gyroscopes.

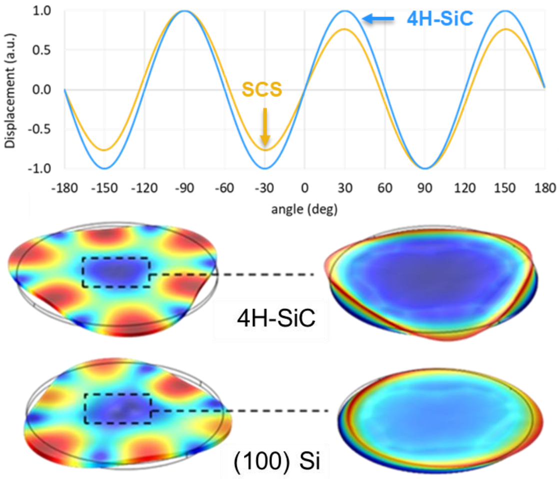

Figure 1: (Top) All antinodes of m=3 mode in 4H-SiC have equal displacement as opposed to the non-uniform mode shape in (100) Si. (Bottom) The central anchor for m=3 mode is symmetrically balanced in 4H-SiC disk while having a net in-plane displacement in (100) Si disk.

DESIGN AND METHOD

BAW disk gyroscope design in 4H-SiC

The elliptical modes in disk resonators are commonly used for capacitive BAW gyroscopes due to their mode degeneracy and high gyroscopic coupling factors [2~7]. In (100) single-crystalline silicon (SCS), the young's modulus is 90° symmetric, resulting in the same angular separation as between the two m=3 modes. However, due to the asymmetry in other directions of SCS lattice, the modal displacements at each of the anti-nodes are different, resulting in a net displacement at the center node, where the resonator will be anchored at. Such displacement will cause a strain energy coupling between the resonator and substrate, leading to the acoustic energy dissipating into the handle layer and significantly reducing Q_{anchor}. More importantly, the substrate coupling makes the resonator sensitive to the mounting conditions and compromises the mode degeneracy. Process variations like anchoring misalignment can introduce excessive stiffness and damping cross-coupling between the two elliptical modes. Hence, anchoring decoupling is necessary for a reliable SCS BAW gyroscope and is typically done by adding a decoupling network near the center node to eliminate stress at the anchor, but at the cost of introducing excessive thermal elastic damping (TED) [3,4]. Though for silicon, the achievable *Q* is limited by the relatively low intrinsic Akhiezer loss before the TED becomes dominant.

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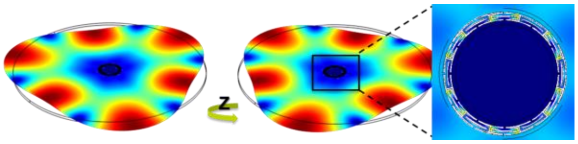

Figure 2: m=3 elliptical mode in 4H-SiC resonator, showing the central decoupling network design.

On the contrary to Si, 4H-SiC possesses hexagonal crystal symmetry. The two m=3 modes have uniform modal displace at all the anti-node with a strain equilibrium at the center anchoring and ideally zero substrate coupling (Figure 1). While a decoupling network is no longer required, a 4H-SiC BAW gyroscope can potentially be designed with a solid disk resonator with minimum TED and eventually reach the Akhiezer limit of $f{\cdot}Q = 6{\times}10^{14}$ Hz.

The ultra-high Q factor significantly reduces the motional impedance, and thus, even with a relatively large gap size, a 4H-SiC BAW resonator can be effectively actuated electrostatically. In addition, large DC voltages can be applied for polarization, which further guarantees the low motional impedance and high electrical scale factor. While the gap size limits the linear displacement range in capacitive parallel plate, it is favorable for a 4H-SiC BAW gyroscope to have a moderate gap to reach a higher mechanical scale factor with a maximum driven amplitude near a few hundred nanometers. Because of the high young's modulus of SiC, the mechanical linearity range can support such a large driving amplitude.

However, the challenge for high stiffness BAW gyroscopes in using a wider capacitive gap is the effective tunning range. The advantage of ultra-high Q in 4H-SiC is only preserved when the two gyroscopic modes are mode matched. To make sure the two m=3 modes can overlap with a limited tunning range, one must design the gyroscope taking into account the process variations that may compromise the mode degeneracy. Therefore, in this work, despite a center decoupling network not being necessary for high Q_{acnhor}, we still put a folded beam network at the center of a 3mm diameter disk resonator to minimize the as-born mode split from the potential process imperfection. The gyroscope mode shape and displacement at the decoupling beam is shown in Figure 2. While a similar design has proven effective in silicon substrate [4], the design is more robust when implemented in 4H-SiC, owing to the symmetric mode shapes. Table 1 highlights the simulated frequency split in 4H-SiC compared to (100) SCS due to common process variations. 24 electrodes with an effective gap size near 2.7µm are uniformly placed around the disk resonator for capacitive transduction and electrostatic tuning. The loaded Q_{TED} is expected to be $9{\times}10^6$ with moderate sidewall roughness, and overall Q should remain higher than the Akheizer limit of Si resonators.

Fabrication

The resonators are fabricated on a 4-inch SiCOI substrate with a device layer thickness of 40µm following a 3-mask process similar to that described in [14]. The SiC device layer is etched through at the wafer level using a Synapse™ module by SPTS, a high-density plasma etch tool designed to etch strongly bonded materials. The SiC DRIE recipe was developed and carried out at SPTS technologies, with the detailed recipe published in [13,15].

Table 1. Frequency split simulation of m=3 BAW disk gyro in (100) Si and 4H-SiC with common process variations

	Frequency split	
Process variation	**(100) Si**	**4H-SiC**
Disk ovalness: 1%	251.91	0.23
Non-vertical trench: 1°	0.65	0.13
Crystal misalignment: 1°	35.77	0.25

Table 2. As born frequency splits and Q factors measured from 10 SiC disk resonators randomly picked across wafer

Device	Δf [ppm]	Q_1 [Million]	Q_2 [Million]
1	0.66	1.803	1.719
2	0.33	1.447	1.531
3	8.3	1.863	1.660
4	3.1	1.492	1.278
5	13.6	2.173	2.008
6	5.2	1.786	1.744
7	2.3	1.356	1.132
8	7.3	1.875	1.368
9	7.3	1.510	1.228
10	6.9	1.633	1.537
Average	***5***	***1.694***	***1.520***

RESULTS AND DISCUSSIONS

Resonator characterization

Over 10 disk resonators across the wafer were characterized and summarized in Table 2, and the as-born frequency response of the resonator showing $Q > 2$M is shown in figure 3. The average as-born frequency split and Q factors are 5ppm and 1.6 million, with good consistency across the wafer. The resonator Q factor is limited by the thermoelastic damping in the decoupling network and surface roughness from the process imperfection, including damage at the top of the SiC DRIE trench due to insufficient mask thickness and some residual surface roughness from grinding (Figure 4).

The mechanical noise equivalent rate (MNEΩ) of a MEMS gyro is inversely proportional to its driving amplitude. The large gaps provided a linear transduction range for studying the 4H-SiC

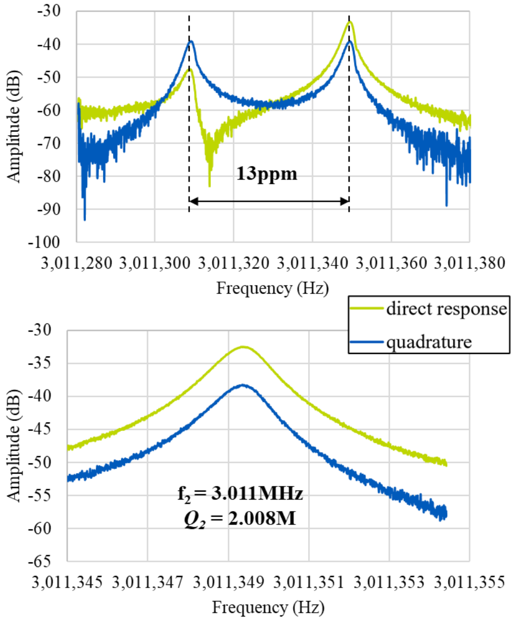

Figure 3: (Top) Large span frequency response of the disk resonator (device 5 from table 2) with highest Q and (Bottom) zoom-in measurement showing Q>2 million. It also shows the worst as-born frequency split in 4H-SiC (13ppm) which is still better than SCS disk resonator with similar design.

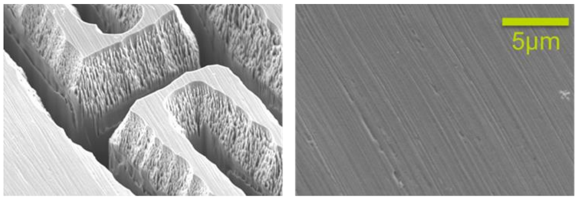

Figure 4: (Left) Roughness at the top of SiC DRIE trench. (Right) Grinding striations on the surface of SiCOI wafer.

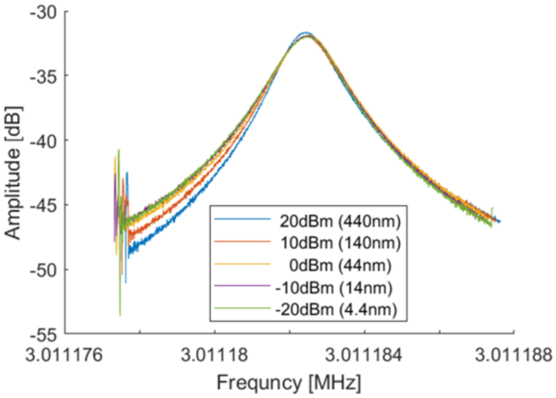

Figure 5: The resonant peak of m=3 mode remains mostly linear with actuation powers up to 20dBm.

resonator linearity under large drive amplitudes. Figure 5 shows the m=3 mode frequency response of a device versus input power. The 4H-SiC resonator is linearly driven up to 440nm, limited by the output supply. The corresponding displacement amplitudes are obtained from FEA simulation.

Gyroscope performance

Two disk resonators with sub-ppm frequency splits were further operated as gyroscopes with similar results. Figure 6 shows one of the gyroscopes wire-bonded on a test circuit board. The two m=3 mode peaks overlap each other within the -3dB bandwidth (Figure 7). Owing to the small as-born mismatch, complete mode matching, including quadrature nulling, can be achieved via electrostatic tuning with 2.7µm gaps. The mode-matched 4H-SiC BAW gyro response was recorded over 1 minute without any noticeable drift, and a linear scale factor of 0.97mV/°/s is measured (Figure 8). The Allan deviation of the device was measured under different driving amplitudes (Figure 9). The lowest angle random walk of 0.03°/√h and BI of 11°/h reported here are from resonator driven with a large amplitude of 350nm.

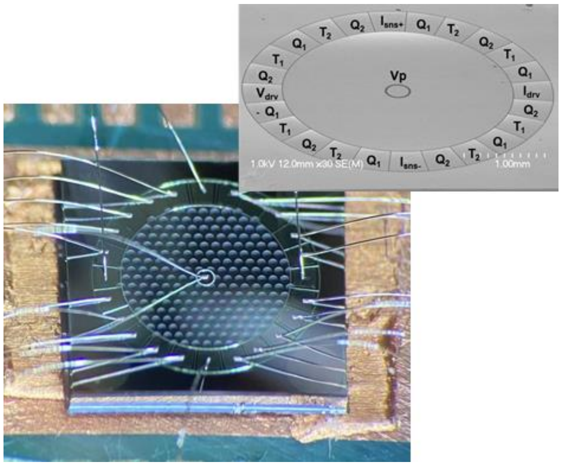

Figure 6: A diced 4H-SiC BAW gyroscope mounted on PCB with all 24 electrodes and center post wire-bonded. The perforated handle layer release pattern can be seen through the transparent SiC device layer. The resonator SEM is shown at inset with electrode configuration labeled.

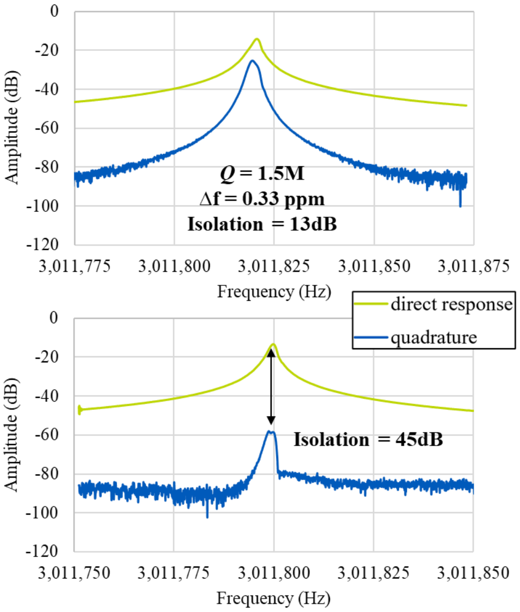

Figure 7: (Top) As-born frequency response of a resonator with 0.33ppm frequency split and 13dB cross-mode isolation (quadrature). (Bottom) The isolation is improved to 45dB with 46V DC tuning voltage applied for quadrature nulling.

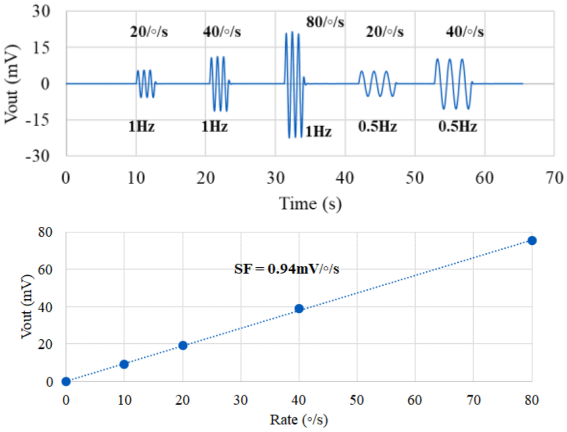

Figure 8: (Top) Output response to different rotation rates at two frequencies in 1 minute. (Bottom) A linear sensitivity of 0.94mV/°/s is measured with 350nm driving amplitude.

Towards navigation grade 4H-SiC BAW gyro

Due to the high tuning voltages required, mode matching and alignment is currently achieved in an open-loop configuration, while the best BI from state of the art silicon BAW gyros are recorded in closed-loop dynamic quadrature tunning [6]. As such, BI of the 4H-SiC gyroscope can be greatly improved with a similar closed-loop quadrature configuration (future work).

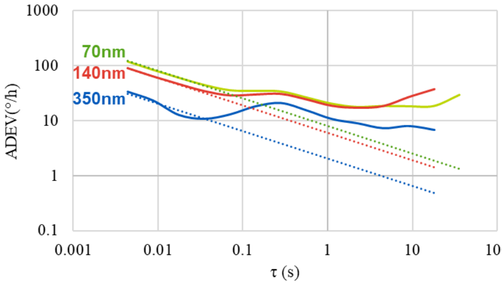

Figure 9: Measured Allan deviation of a SiC BAW gyroscope, the angle random walk (ARW) with -0.5 slope linear fit is measured to be 0.13°/√h, 0.09°/√h, and 0.03°/√h with 70/140/350nm excitation amplitude for the 3mm disk.

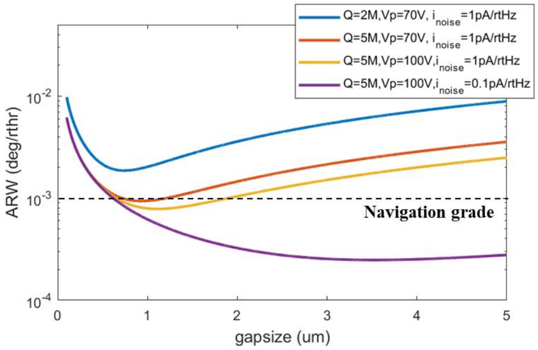

Figure 10: The projected ARW of a 3MHz 4H-SiC BAW disk resonant gyroscope with improved Q, DC bias voltage, and circuit noise, exceeding the navigation grade when maximally driven to a tenth of its capacitive gap size.

It is also worth noting that as the driving power increases, flicker noise becomes more dominant in the overall BI, as the input-referred noise scales with the AC actuation voltage. While the gyroscope is maximumly driven to minimize the mechanical noise equivalent rate, a high-performance gyroscope requires the electrical noise equivalent rate (ENEΩ) to be in a comparable range. This can be done by improving the input-referred noise of the interfacing circuit, increasing the polarization DC voltage, and further improving the *Q* factor. The demonstrated *Q* is compromised by the trench damage at the decoupling network, which induced excessive TED; there is still a lot of room for *Q* improvement before reaching the Akhiezer limit. While the total noise is a function of gap size (and driving amplitude), Figure 10 predicts the expected noise performance under different conditions.

CONCLUSION

We reported the gyroscope performance of capacitive BAW disk resonators fabricated at wafer level on 4H-SiC on insulator substrate for the first time. The 4H-SiC disk resonators consistently show small frequency splits between the two gyroscopic m=3 elliptical modes, which relaxes the electrostatic tunning requirement and allows for complete mode matching even with a relatively large 2.7μm transduction gap. The average *Q* of 1.5 million demonstrated in this work is challenging to achieve in a similar design in (100) Si and can be further improved by improving the fabrication process. The large transduction gap size defined by DRIE allows a large linear actuation range for higher scale factor and SNR, demonstrating an ARW of 0.03°/√h. The measured bias instability is relatively large, which is attributed to lack of closed-loop quadrature nulling and un-optimized electronics, expected to improve substantially.

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